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COMPUTER STUDY OF SUBSIDIARY RESONANCE PHENOMENA IN MICROWAVE MAGNETIC MATERIALS

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May 1968

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COMPUTER STUDY OF SUBSIDIARY RESONANCE PHENOMENA IN MICROWAVE MAGNETIC MATERIALS

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Abstract

A computer study at X-band frequencies of the threshold fields for subsidiary resonance phenomena in a wide range of magnetic materials has been conducted. The variation of the critical power for spin-wave excitation has been determined as a function of the material parameters combined with the geometry of the ferrite material. The investigation has shown that, at a given frequency, low-level operation of microwave devices that utilize subsidiary resonance absorption requires a material with a very narrow spin-wave linewidth and a saturation magnetization in the order of 5000 gauss. The optimum material geometry that yields the lowest threshold is the case where the demagnetizing factor $N_z = 0$, where z represents the direction of the applied dc field, and the transverse demagnetizing factors N_x and N_y are equal to 0.5.

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COMPUTER STUDY OF SUBSIDIARY RESONANCE PHENOMENA IN MICROWAVE MAGNETIC MATERIALS

INTRODUCTION

The nonlinear properties of ferrites and garnets have been utilized in the fabrication of numerous forms of subsidiary resonance limiters.[1,2] This type of limiter offers advantages of being simple to construct and has an inherently broader frequency bandwidth. However, it has the disadvantage of having the highest threshold power. Subsidiary resonance absorption is a so-called first-order nonlinear effect because it arises from the coupling between certain spin waves and the uniform precession. First-order effects involve only spin waves that are one-half the frequency of the applied signal, $\omega_k = \omega/2$, where ω_k is the spin wave frequency, and ω is the frequency of operation. Subsidiary resonant absorption is normally observed at a dc field that is below the field required for ferrimagnetic resonance. The result of this nonresonant excitation yields a threshold field that is relatively high.

Because of the inherently broader frequency bandwidth of subsidiary resonance limiters, this report concerns itself with the methods of reducing the threshold power. A Burroughs 5500 Digital Computer was utilized in optimizing the geometry and material parameters to obtain the lowest possible threshold power.

ANALYTICAL PROCEDURE

The appearance of the subsidiary resonance at high power levels is governed by the condition that:[3]

$$\gamma H_{dc} < \frac{\omega}{2} + N_z \omega_m \tag{1}$$

where γ = gyromagnetic ratio = 2.8,

H_{dc} = applied dc field,

ω = operating frequency,

N_z = demagnetizing factor,

and ω_m = $\gamma 4\pi M$ = saturation magnetization of the material.

These restrictions assure that the dc biasing field has been reduced sufficiently so that the half-frequency spin waves ($\omega_k = \omega/2$) required for first-order nonlinear process will exist. When this condition is satisfied, the threshold field for excitation of half-frequency spin waves is given by the following:

$$h_c = \frac{2\omega\Delta H_k \left[(\omega - \omega_r)^2 + (\gamma\Delta H)^2\right]^{1/2}}{\omega_m \left(\frac{\omega}{2} + \omega_H - N_z\omega_m\right)} \tag{2}$$

where h_c = critical field,

ΔH_k = spin-wave linewidth,

ω_r = Kittel resonant frequency,

ΔH = resonant linewidth,

and $\omega_H = \gamma H_{dc}$.

The material parameters that have a significant effect in reducing the threshold are the spin-wave linewidth, the saturation magnetization, the demagnetizing factors, and the frequency of operation.

Ten different materials were investigated utilizing the computer for detailed calculations. The magnetic materials had saturation magnetizations that ranged from 250 to 6000 gauss and spin-wave linewidths that varied from 0.09 to 2.0 oersteds.

Four geometries were considered that yielded four different sets of demagnetizing factors. The resonance frequency of the ferrite material is influenced by the demagnetizing fields and is given by:[4]

$$\omega = \left[\gamma H_{dc} + (N_x - N_z)\,\omega_m\right]^{1/2} \left[\gamma H_{dc} + (N_y - N_z)\,\omega_m\right]^{1/2} \tag{3}$$

where N_x, N_y, and N_z are the demagnetizing factors in cartesian coordinates. The demagnetizing factors arise in the following way: When an external field is applied to a homogenous specimen, magnetic dipoles are induced at the surface and create a component of magnetic field opposing the original field. The internal field, H_i, is given by:

$$H_i = H_{dc} - N\,(4\pi M) \tag{4}$$

where $N\,(4\pi M)$ is an opposing internal field caused by the presence of dipoles induced on the surface. The demagnetizing factor, N, is a measure of this induction and depends on the geometry of the ferrite material.

There are several special geometrical shapes that are of primary interest and will recur frequently in the discussion of microwave devices. These special shapes are ellipsoid, needle, sphere, and thin discs.

The method used to obtain the various curves and tables illustrated in this report was to program equations (2) and (3) along with the restrictions listed in equation (1) into the computer. Values of h_c were obtained as a function of applied dc field for the frequency range (8.4 to 12.4 GHz) for each material.

Since the interest was to determine the conditions for minimum h_c, the effect of demagnetizing factors on the limiting threshold of polycrystalline yttrium-iron-garnet (YIG) material was first investigated to limit the number of cases to be studied. Equation (2) was programmed into the computer with equation (3) substituted for ω_k in equation (2). With all other parameters held constant, minimums of h_c were obtained as a function of demagnetizing factors.

RESULTS

The effect of the demagnetizing factors on the critical field for subsidiary resonance is presented in Table I, a. through d. Each table has a constant N_z with the transverse demagnetizing factors, N_x and N_y, changing such that the sum $N_x + N_y + N_z$ always equals 1.0. These tables indicate the geometry that will result in a minimum threshold field for a constant set of material parameters. The data presented in the tables are computed for polycrystalline YIG material. The critical field is tabulated for four values of N_z (0.0, 0.3, 0.5, 1.0), while N_x and N_y are changed over the allowable range ($1-N_z$) for each value of N_z. The data were computed at the center frequency of X band, 10.4 GHz.

The following conclusions can be made from the data presented in the tables:

a. The critical field is a direct function of N_z. The minimum value of 0.3622 oersted is obtained for $N_z = 0$, $N_x = 0.5$, and $N_y = 0.5$, and the maximum value of 2.4470 oersteds is obtained for $N_z = 1.0$ and $N_x = N_y = 0$.

b. The transverse demagnetizing factors, N_x and N_y, have only a secondary effect on critical field. The critical field value changes by less than 15% when N_x and N_y are varied over the range of 0 to 1. When N_z is changed over the same range, the critical field changes by almost an order of magnitude.

c. The minimum critical field for a given value of N_z is found for $N_x = N_y$.

The effects of material parameters and geometry on the critical field are tabulated in Tables II through V. The minimum value of h_c was computed for three frequencies, 8.4, 10.4, and 12.4 GHz in the X-band range. The material properties, such as $4\pi M_s$, ΔH_k, and ΔH, are listed for each specimen. The ten magnetic materials considered were as follows: single

TABLE I - The Critical Field (h_c) for Polycrystalline YIG at a Constant Frequency of 10.4 GHz as a Function of Demagnetizing Factors (Geometry).

N_x	N_y	N_z	h_c
0.0	1.0	0.0	0.4134
0.1	0.9	0.0	0.3496
0.2	0.8	0.0	0.3803
0.3	0.7	0.0	0.3702
0.4	0.6	0.0	0.3642
0.5	0.5	0.0	0.3622
0.6	0.4	0.0	0.3642
0.7	0.3	0.0	0.3702
0.8	0.2	0.0	0.3803

a.

N_x	N_y	N_z	h_c
0.0	0.7	0.3	0.7845
0.1	0.6	0.3	0.7638
0.2	0.5	0.3	0.7504
0.3	0.4	0.3	0.7438
0.35	0.35	0.3	0.7388
0.4	0.3	0.3	0.7438
0.5	0.2	0.3	0.7504
0.6	0.1	0.3	0.7638

b.

N_x	N_y	N_z	h_c
0.0	0.5	0.5	1.1097
0.1	0.4	0.5	1.0884
0.2	0.3	0.5	1.0780
0.25	0.25	0.5	1.0730
0.3	0.2	0.5	1.0780
0.4	0.1	0.5	1.0884

c.

N_x	N_y	N_z	h_c
0.0	0.0	1.0	2.4470

d.

TABLE II - Critical Fields (h_c) and Material Parameters for Each Sample Investigated Utilizing the Needle Geometry.

MATERIAL	$4\pi M_s$ (gauss)	ΔH_k (Oe)	ΔH (Oe)	Minimum h_c (Oe) 8.4 GHz	10.4 GHz	12.4 GHz
Poly-Xtal YIG	1750	0.3	44	0.2	0.36	0.52
Single-Xtal YIG	1750	0.1	0.3	0.06	0.11	0.115
$Y_3Al_{0.33}Fe_{4.67}O_{12}$	1200	2.0	60	3.0	4.4	4.4
$Y_3AlFe_4O_{12}$	550	1.0	75	4.2	6.0	6.1
$Mn_{0.5}Zn_{0.5}Fe_2O_4$	6000	2.0	30	0.04	0.12	0.06
$Ni_{0.5}Zn_{0.5}Fe_2O_4$	5000	1.2	5	0.04	0.02	0.06
Li Ferrite	3800	0.5	1	0.02	0.01	0.02
$Eu_3Fe_{3.72}Ge_{1.28}O_{12}$	250	0.11	190	1.2	1.6	1.6
TT-414 (Mg,Mn(Al))	650	0.13	160	0.64	0.82	0.82
R-1 (Mg,Mn)	2100	0.09	505	0.06	0.09	0.09

$N_z = 0 \quad N_x = 0.5 \quad N_y = 0.5$

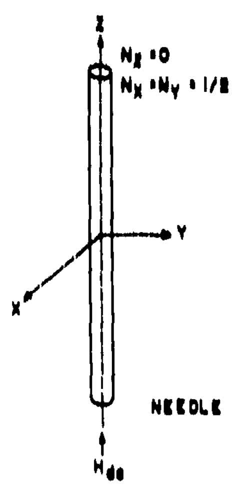


TABLE III - Critical Fields (h_c) and Material Parameters for Each Sample Investigated Utilizing the Ellipsoidal Geometry.

MATERIAL	$4\pi M_s$ (gauss)	ΔH_k (Oe)	ΔH (Oe)	Minimum h_c (Oe) 8.4 GHz	10.4 GHz	12.4 GHz
Poly-Xtal YIG	1750	0.3	44	0.35	0.5	0.65
Single-Xtal YIG	1750	0.1	0.3	0.11	0.15	0.21
$Y_3Al_{0.33}Fe_{4.67}O_{12}$	1200	2.0	60	4.0	5.4	6.8
$Y_3AlFe_4O_{12}$	550	1.0	75	4.8	6.4	8.0
$Mn_{0.5}Zn_{0.5}Fe_2O_4$	6000	2.0	30	0.01	0.25	0.55
$Ni_{0.5}Zn_{0.5}Fe_2O_4$	5000	1.2	5	0.15	0.35	0.4
Li Ferrite	3800	0.5	1	0.28	0.4	0.52
$Eu_3Fe_{3.72}Ge_{1.28}O_{12}$	250	0.11	190	1.4	1.8	1.8
TT-414 (Mg,Mn(Al))	650	0.13	160	0.75	0.9	1.1
R-1 (Mg,Mn)	2100	0.09	505	0.15	0.18	0.24

$N_z = 0.5 \quad N_x = 0.25 \quad N_y = .0.25$

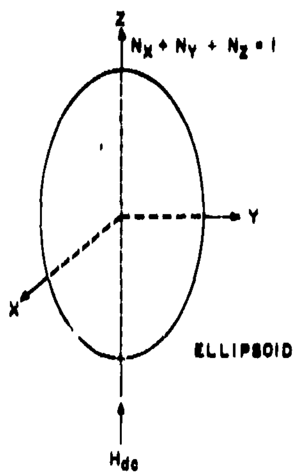


TABLE IV - Critical Fields (h_c) and Material Parameters for Each Sample Investigated Utilizing the Spherical Geometry.

MATERIAL	$4\pi M_s$ (gauss)	ΔH_k (Oe)	ΔH (Oe)	Minimum h_c (Oe) 8.4 GHz	10.4 GHz	12.4 GHz
Poly-Xtal YIG	1750	0.3	44	0.3	0.44	0.6
Single-Xtal YIG	1750	0.1	0.3	0.1	0.16	0.2
$Y_3Al_{0.33}Fe_{4.67}O_{12}$	1200	2.0	60	4.1	5.6	7.1
$Y_3AlFe_4O_{12}$	550	1.0	75	5.8	7.4	7.4
$Mn_{0.8}Zn_{0.2}Fe_2O_4$	6000	2.0	30	0.1	0.36	0.36
$Ni_{0.5}Zn_{0.5}Fe_2O_4$	5000	1.2	5	0.02	0.2	0.6
Li Ferrite	3800	0.5	1	1.35	1.75	1.75
$Eu_3Fe_{3.72}Ga_{1.28}O_{12}$	250	0.11	190	0.09	0.19	0.35
TT-414 (Mg,Mn(Al))	650	0.13	160	0.46	0.64	0.82
R-1 (Mg,Mn)	2100	0.09	505	0.09	0.13	0.13

$N_z = 0.33 \quad N_x = 0.33 \quad N_y = 0.33$

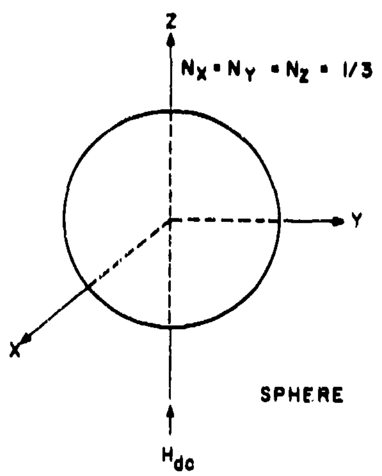
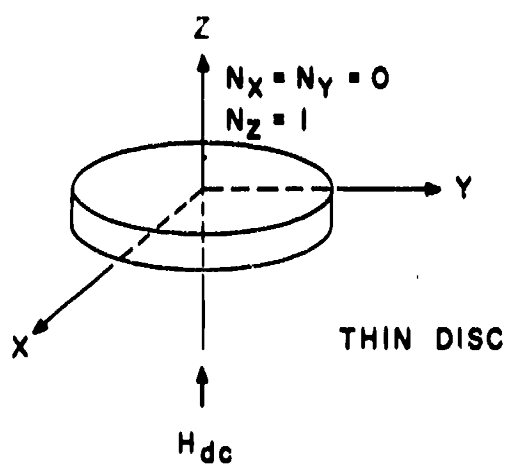


TABLE V - Critical Fields (h_c) and Material Parameters for Each Sample Investigated Utilizing the Thin Disc Geomotry.

MATERIAL	$4\pi M_s$ (gauss)	ΔH_k (Oe)	ΔH (Oe)	8.4 GHz	10.4 GHz	12.4 GHz
Poly-Xtal YIG	1750	0.3	44	0.65	0.8	0.96
Single-Xtal YIG	1750	0.1	0.3	0.20	0.25	0.25
$Y_3Al_{0.33}Fe_{4.67}O_{12}$	1200	2.0	60	4.5	6.0	6.1
$Y_3AlFe_4O_{12}$	550	1.0	75	5.7	7.3	7.3
$Mn_{0.8}Zn_{0.2}Fe_2O_4$	6000	2.0	30	0.65	0.90	1.2
$Ni_{0.5}Zn_{0.5}Fe_2O_4$	5000	1.2	5	0.70	0.90	1.15
Li Ferrite	3800	0.5	1	0.48	0.60	0.59
$Eu_3Fe_{3.72}Ga_{1.28}O_{12}$	250	0.11	190	1.50	1.9	1.9
TT-414 (Mg,Mn(Al))	650	0.13	[illegible]0	0.50	0.68	0.86
R-1 (Mg,Mn)	2100	0.09	505	0.13	0.17	0.18

$N_z = 1.0 \quad N_x = 0 \quad N_y = 0$



and polycrystalline YIG, single-crystal manganese and nickel-zinc ferrite, single-crystal lithium ferrite, single-crystal gallium substituted europium irongarnet, Trans-Tech 414, General Ceramics R-1, and two compositions of aluminum substituted YIG. These compositions were utilized in the study because they gave the widest range of variation in material properties. In addition to the optimum case where $N_z = 0$ and N_x and $N_y = 0.5$ (Table II), the calculations were carried out for three other combinations of demagnetizing factors (Tables III through V). The other cases were considered for comparison since, in the development of a practical limiter, other factors may dictate the sample geometry.

The data presented in Table II for the optimum demagnetizing factors illustrate how the critical field depends on material parameters. At the center frequency of 10.4 GHz the critical field varies over a range of 0.01 to 4.4 oersteds. The two most important material parameters are saturation magnetization ($4\pi M_s$) and spin-wave linewidth (ΔH_k). The fact that the critical field is not sensitive to the uniform precession linewidth (ΔH) is demonstrated by single-crystal YIG and polycrystalline R-1 material, which have nearly the same critical field of 0.10 oersted at the center frequency of 10.4 GHz, while YIG has a resonance linewidth of 0.3 oersted compared to 505 oersteds for R-1. The lowest h_c in Table II is 0.01 oersted for lithium ferrite at 10.4 GHz. In Tables III, IV, and V the critical fields for lithium ferrite are 0.4, 1.75, and 0.60 oersteds respectively. This pattern in general is repeated at all frequencies for each material.

The frequency dependence of the critical field is an important consideration in the development of broadband limiters. The variation of critical field with frequency can be determined from Figure 1:

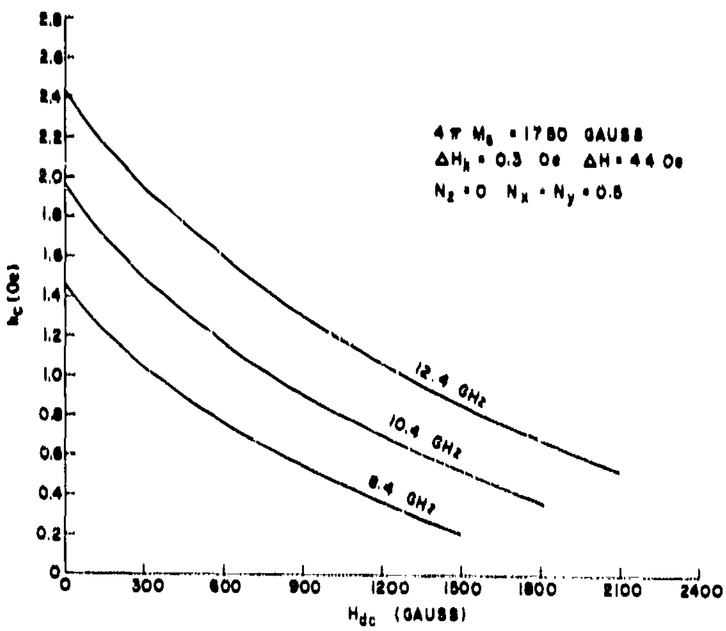


Figure 1. Variation of h_c vs. H_{dc} with frequency as the parameter.

The critical field is plotted as a function of dc biasing magnetic field over the allowed range with frequency as a parameter. The curves are plotted for polycrystalline YIG material for the optimum geometry ($N_z = 0$, $N_x = N_y = 0.5$). The lowest critical field is obtained when the limiter is biased at a dc magnetic field of 1500 oersteds. With this bias field the variation of critical field is 0.66 oersted over the frequency range of 8.4 to 12.4 GHz. The separation of curves is essentially linear with a variation of 0.165 oersted/GHz. This frequency sensitivity limits the application of subsidiary resonance limiters. The results in Figure 1 also illustrate that it is desirable to operate at the highest magnetic biasing field consistent with the limitations imposed by equation (1) since this results in the lowest critical field over the desired frequency band.

The influence of spin-wave linewidth on the critical field is demonstrated in Figure 2:

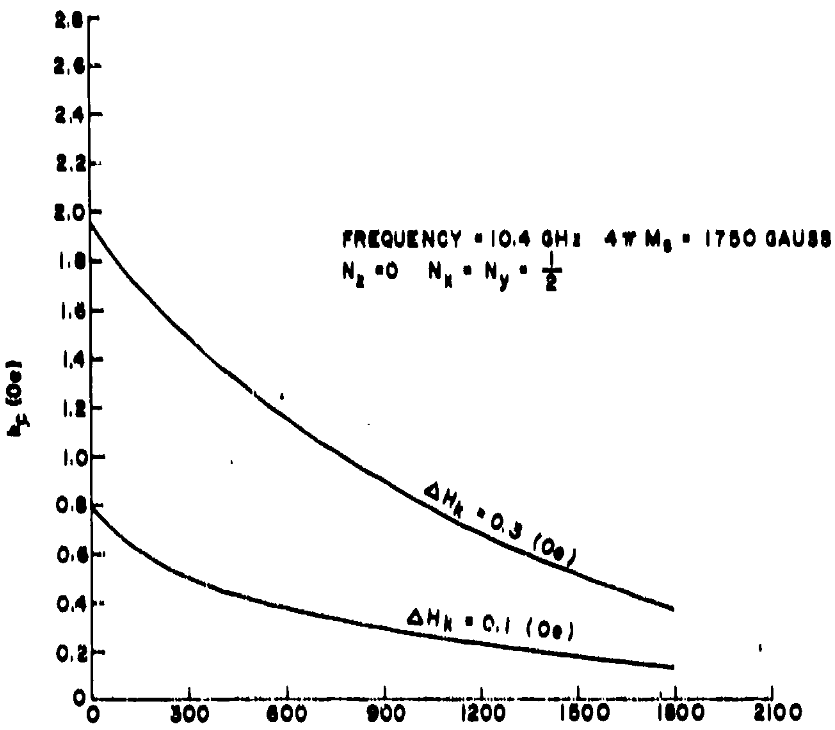


Figure 2. Variation of h_c vs. H_{dc} with ΔH_k as the parameter.

The critical field is plotted as a function of dc magnetic biasing field with the spin-wave linewidth, ΔH_k, as a parameter. In Figure 3 the same function is plotted with the saturation magnetization ($4\pi M_s$) as a parameter:

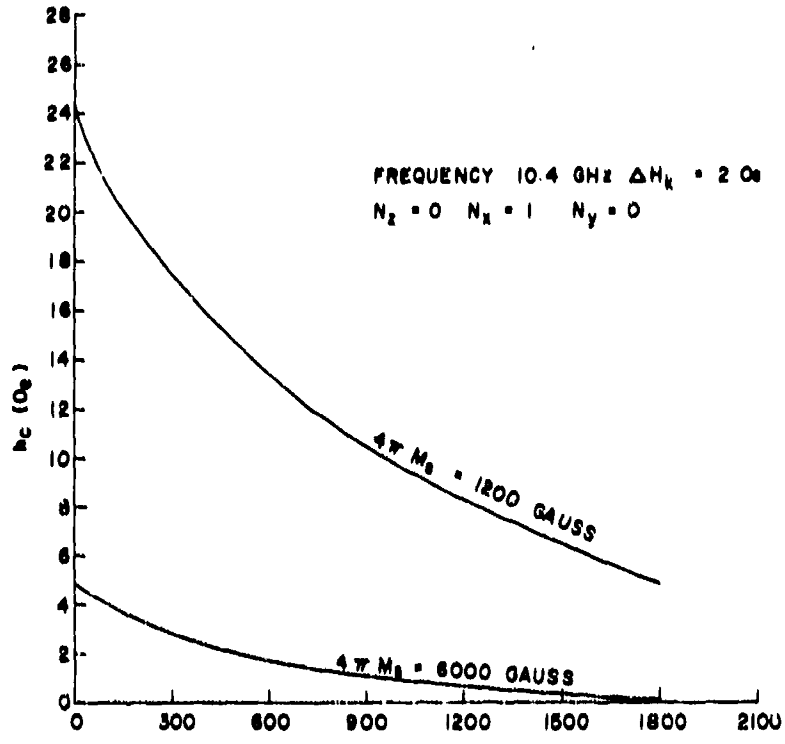


Figure 3. Variation of h_c vs. H_{dc} with $4\pi M_s$ as the parameter.

The information indicates that drastic reductions in threshold fields can be achieved by reducing the spin-wave linewidth and increasing the saturation magnetization of the ferrite material.

CONCLUSIONS

Information has been obtained concerning the critical field (h_c) for the subsidiary resonance absorption phenomena with regard to material parameters, such as resonance linewidth (ΔH), spin-wave linewidth (ΔH_k), and the saturation magnetization ($4\pi M_s$). In addition, these data have been combined with geometry considerations that affect the demagnetizing factors. The investigation has shown that, at a given frequency, low-level operation of microwave devices that utilize subsidiary resonance absorption will require a material with a very narrow spin-wave linewidth coupled with a high saturation magnetization. The material geometry that generally yields the smallest threshold is the needle, where $N_z = 0$ and N_x and $N_y - 0.5$.

This information shows that the designs of all existing ferrite limiters are not utilizing the optimum geometry. This is true since other considerations, such as waveguide filling factor, weight of biasing magnet, and ease of fabrication have dictated the geometry of the ferrite sample. The results of this computer study show that the threshold power level can be reduced by an order of magnitude by optimizing the ferrite geometry. This improvement makes it worthwhile to solve the complex design problems connected with the use of the optimum ferrite geometry.

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13. ABSTRACT

A computer study at X-band frequencies of the threshold fields for subsidiary resonance phemomena in a wide range of magnetic materials has been conducted. The variation of the critical power for spin-wave excitation has been determined as a function of the material parameters combined with the geometry of the ferrite material. The investigation has shown that, at a given frequency, low-level operation of microwave devices that utilize subsidiary resonance absorption requires a material with a very narrow spin-wave linewidth and a saturation magnetization in the order of 5000 gauss. The optimum material geometry that yields the lowest threshold is the case where the demagnetizing factor $N_z = 0$, where z represents the direction of the applied dc field, and the transverse demagnetizing factors N_x and N_y are equal to 0.5. (Authors)

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